Radial truncations in stellar discs in galaxies

Kregel, M.; van der Kruit, P. C.

Published in:
Monthly Notices of the Royal Astronomical Society

DOI:
10.1111/j.1365-2966.2004.08307.x

Mon. Not. R. Astron. Soc. **355,** 143–146 (2004) doi:10.1111/j.1365-2966.2004.08307.x

Radial truncations in stellar discs in galaxies

M. Kregel and P. C. van der Kruit★
Kapteyn Astronomical Institute, University of Groningen, PO Box 800, 9700AV Groningen, the Netherlands

Accepted 2004 August 11. Received 2004 August 6; in original form 2004 June 10

ABSTRACT

We discuss the possible origin of the radial truncations in stellar discs, using measurements that we presented in an earlier paper. A tentative correlation is found with the de-projected face-on central surface brightness; lower surface brightness discs tend to have a smaller truncation radius in units of scalelength. This and our earlier finding that in smaller spirals the truncation tends to occur at a larger number of scalelengths are best reproduced when the truncation is caused by a constant gas-density threshold on star formation.

Key words: galaxies: fundamental parameters – galaxies: spiral – galaxies: structure.

1 INTRODUCTION

Stellar discs have a finite size. In the extreme outer parts the stellar light distribution diminishes more steeply than the exponential decline over the main disc and drops to low values beyond the so-called truncation radius $R_{\rm max}$ (van der Kruit 1979, van der Kruit & Searle 1981a,b, 1982, hereafter KS1–3; Pohlen et al. 2000; Schwarzkopf & Dettmar 2000; de Grijs, Kregel & Wesson 2001, hereafter GKW; Florido et al. 2001). This truncation or cut-off of the disc light is often directly visible in contour maps of edge-on spirals and usually occurs at a radius of 3–5 disc scalelengths (van der Kruit 2001a), although stellar discs that extend to a much larger number of scalelengths are certainly known to exist (e.g. Weiner et al. 2001). The truncation is most easily found in edge-on spirals because of the line-of-sight projection and the associated higher surface brightness.

In less inclined spirals, for which azimuthally averaged radial light profiles are routinely studied, the non-axisymmetric component (e.g. spiral structure, lopsidedness) can smooth out a truncation present in the old disc. This effect was first noted by van der Kruit (1988). For 16 face-on spirals, of which 15 did not show any sign of a truncation in the azimuthally averaged light profile, he found that the three outermost isophotes were much more closely spaced than the inner ones, providing clear evidence for the truncation. The Milky Way disc probably also shows a truncation, with recent estimates of $R_{\rm max}$ ranging from 10 to 15 kpc based on near-infrared star counts (Ruphy et al. 1996) and the near- and far-infrared sky survey of the *COBE*/DIRBE instrument (Freudenreich 1998; Drimmel & Spergel 2001). Recently, wide-field surveys have also revealed truncations in the Local Group galaxies NGC 2403 (Davidge 2003) and NGC 3109 (Demers et al. 2003).

The origin of the truncation of the stellar disc is still unclear and could possibly result from a number of physical scenarios (van der Kruit 2001a; Freeman 2002). For example, if there has been no major redistribution of the disc angular momentum during its formation and evolution, the truncation may reflect the maximum specific angular momentum of the protogalaxy (van der Kruit 1987). This would imply that the H I extending beyond the stellar disc (e.g. Broeils & Rhee 1997) has been accreted, and that the truncation is associated with a small drop in the rotation curve (KS3; Bottema 1996). Another interesting possibility is that the truncation corresponds to the radius at which the gas density drops below a threshold density necessary for star formation (Fall & Efstathiou 1980; KS3; Kennicutt 1989; Schaye 2004).

In Kregel et al. (2002, hereafter KKG) we fitted truncation radii to the photometry of 34 edge-on galaxies from the sample of de Grijs (1997, 1998). The selection criteria and properties of this sample are summarized in KKG (section 2 and table 1). The sample covers a large range in rotation velocity ($v_{\rm max} = 50$–400 km s^{-1}) and is dominated by spirals of intermediate- to late-type. Of the 34 galaxies we found that at least 20 have truncated discs. The truncation radii $R_{\rm max}$ have been listed in table 5 in KKG. Here we further compare the observed truncation radii to those predicted by the scenarios proposed for the origin of the truncation, and specifically address the behaviour with disc surface brightness (see also Kregel 2003).

2 THE TRUNCATION RADIUS VERSUS DISC PARAMETERS

We show the distribution of $R_{\rm max}/h_{\rm R}$ versus scalelength in Fig. 1(a). For those galaxies for which no truncation was found, the lower limit is shown (arrows). Fig. 1(a) appears to show a subtle increase in $R_{\rm max}/h_{\rm R}$ towards small scalelengths; the average ratio for the spirals with $h_{\rm R} < 4$ kpc is 4.4, more than one standard deviation higher than that of the entire sample. This increase of $R_{\rm max}/h_{\rm R}$ may be related to its decrease found at very large scalelengths by Pohlen, Dettmar & Lütticke (2000). However, the reality of this feature is not entirely clear considering the modest sample size and the selection effect against galaxies of small physical sizes and low surface brightness. We are, for example, still missing small low surface

★E-mail: vdkruit@astro.rug.nl

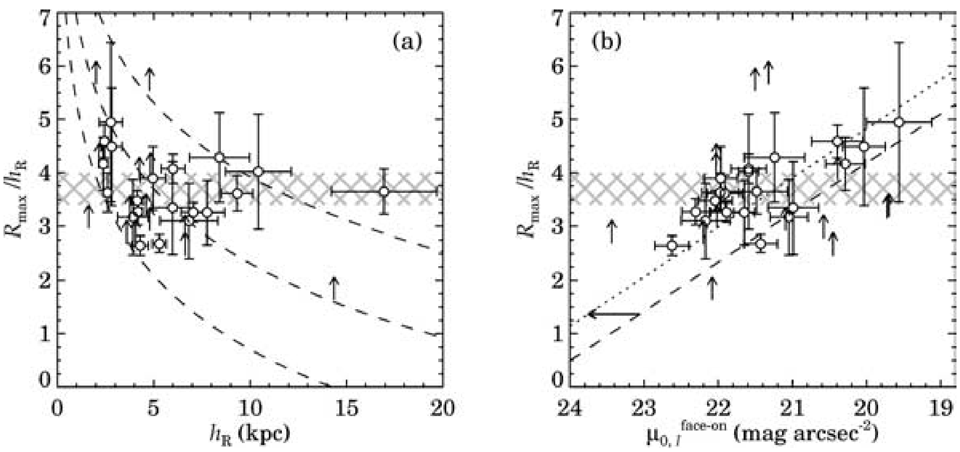

Figure 1. (a) R_{max}/h_R versus disc scalelength. The arrows indicate lower limits for galaxies for which no R_{max} could be determined. The cross-hatched region shows the prediction of the collapse model for disc-galaxy formation (see text). The dashed lines show the predicted threshold radii for star formation (Schaye 2004) for disc masses of, from bottom to top, 7.5×10^9, $5 \times 7.5\,10^9$ and $25 \times 7.5\,10^9$ M$_\odot$. (b) R_{max}/h_R versus face-on central surface brightness in the *I*-band. The arrows and the cross-hatched region are as in (a). The dashed line shows the constant star-formation threshold prediction. The shifted dotted line is obtained when allowing for an underestimation of the surface brightnesses by 0.7 mag (see text).

brightness galaxies, which may have entirely different R_{max}/h_R. While our view of the distribution of R_{max}/h_R is certainly obscured by this selection effect, additional information can be obtained from face-on samples. We have estimated a lower limit to R_{max} for the spirals in the face-on sample of de Jong & van der Kruit (1994), a sample which is dominated by spirals of small scalelength. By taking the lowest contour in their *R*-band contour plots as a lower limit to R_{max}, we find an average $(R_{max}/h_R)_{min} = 4.0 \pm 1.1$ (1σ). This lower limit and the tentative increase of R_{max}/h_R towards small-scalelength spirals suggest that the ratio of truncation radius to disc scalelength in small scalelength nearby spirals is at least four.

Fig. 1(b) shows the dimensionless truncation radius versus the deprojected face-on central surface brightness (corrected for Galactic extinction as in de Grijs 1998). The ratio R_{max}/h_R appears to be correlated with surface brightness in the sense that lower surface brightness discs tend to truncate at a smaller number of scalelengths. A Spearman rank correlation test appears conclusive, yielding a correlation coefficient of 0.61 (or a confidence level greater than 99 per cent). However, the errors are substantial in many cases and not entirely random, so that the test could have given a false positive result. Note that the face-on surface brightnesses are probably underestimated, by ~ 0.7 mag according to a comparison between the Tully–Fisher relations of edge-on and face-on spirals (Kregel, van der Kruit & Freeman 2004; hereafter Paper V). The large lower limits for ESO 340-G08 and ESO 555-G36 are puzzling. The discs of these spirals appear to be far more extended than the norm.

Figs 1(a) and (b) combined suggest that in small-scalelength, high surface brightness spirals the truncation occurs at at least four scalelengths. This is important, because small spirals ($h_R \lesssim 4$ kpc) are the most numerous in the local Universe (van der Kruit 1987; de Jong & Lacey 2000, KKG). As another corollary, the range in face-on surface brightness among spirals is narrower at R_{max} than at the disc centre. If the discs in the current sample are exponential out to R_{max} then the distribution of *I*-band face-on surface brightnesses at R_{max} has an average of 25.3 mag arcsec^{-2} and a 1σ scatter of 0.6 mag arcsec^{-2}. This dispersion is considerably smaller than the 1.1 mag arcsec^{-2} dispersion in the central surface brightness. This also implies that in the face-on view, the truncation is just as easily (or laboriously) detected in low surface brightness (LSB) as in high surface brightness (HSB) spirals.

3 COMPARISON WITH HYPOTHESES FOR THE ORIGIN OF THE TRUNCATIONS

We can compare the observed trends to the predictions of the analytical collapse model of disc galaxy formation (Fall & Efstathiou 1980; Gunn 1982; Dalcanton, Spergel & Summers 1997, hereafter DSS97). If protogalaxies are relatively sharp-edged, then the collapse theory also predicts the outermost radius of the baryonic disc (van der Kruit 1987). This radius corresponds to the material with the highest specific angular momentum in the protogalaxy. To quantify this prediction we calculated model surface density profiles using the method of DSS97 for a range in spin parameter and total mass of the protogalaxy. We assume a constant baryonic mass fraction $F = 0.10$ and a constant efficiency for turning the baryons into stars over the age of the disc at $(M/L)_{disc} = 2$ (see Paper V). The scalelengths were derived using a method similar to the 'marking-the-disc' method (Freeman 1970), and the outermost radii were obtained by taking the radius at which the density drops to zero. The result is indicated by the cross-hatched region in Fig. 1.

In the collapse theory, both the outermost radius and the scalelength of the baryonic protodisc increase with the mass and angular momentum of the protogalaxy such that their ratio remains approximately constant at 3–4. Taking a different or non-constant baryon mass fraction does not significantly change this result. The predicted R_{max}/h_R is slightly smaller than the ratio of 4.5 predicted by van der Kruit (1987) based on a comparison of the angular momentum distribution of an exponential disc with that of a uniformly rotating, uniform sphere with $\lambda = 0.07$. Although the prediction of the collapse model roughly coincides with the average observed R_{max}/h_R, it cannot explain the existence of discs which extend to a relatively large or a small number of scalelengths. In particular, it does not predict an increase of R_{max}/h_R toward small scalelengths (Fig. 1a), or a decrease towards low surface brightness discs (Fig. 1b). Taking a different halo density profile and/or angular momentum profile could change the value of R_{max}/h_R, but not its constancy. Including additional prescriptions for mass accretion, star formation and supernova feedback can lead to R_{max}/h_R ratios that do change as a function of central surface brightness, but with the opposite sign (van den Bosch 2001). Perhaps taking a range in angular momentum profiles, as suggested by *N*-body simulations in the ΛCDM cosmology (Bullock et al. 2001), or redistributing the angular momentum during and/or after the collapse could resolve the discrepancy.

Alternatively, the stellar disc truncation may be caused by the inhibition of widespread star formation below a critical gas surface density (Fall & Efstathiou 1980; KS3; Kennicutt 1989), *if* the corresponding critical radius is approximately constant over time. This star-formation threshold is suspected to be related to the stability of the gas disc. Recently, Schaye (2004) made a prediction for the threshold radius based on simulations of the thermal and ionization structure of the gaseous discs assembled in the galaxy-formation model of Mo, Mao & White (1998). In these simulations the transition to the cold interstellar medium (ISM) phase is responsible for the onset of local gravitational instability that triggers star formation. This transition to the cold phase is independent of the shape of the rotation curve and occurs at a critical gas surface density, which for reasonable values of the gas fraction, turbulence, metallicity and the ultraviolet (UV) radiation intensity, attains values in the range $\Sigma_c \sim 3$–$10\ \mathrm{M_\odot\ pc^{-2}}$ (Schaye 2004). For a disc with an exponential surface density profile, he finds:

$$\frac{R_{\max}}{h_R} = \ln \frac{M_{\rm disc}}{2\pi h_R^2 \Sigma_c}, \tag{1}$$

where $M_{\rm disc}$ is the disc mass (gas and stars) and h_R is the mass scalelength. It is easy to show that when the gas mass is negligible this prediction reduces to:

$$\frac{R_{\max}}{h_R} = \ln \frac{(M/L)_\star \mu_0}{\Sigma_c} \tag{2}$$

with $(M/L)_\star$ the stellar mass-to-light ratio and μ_0 its central surface brightness (linear units).

The predicted threshold radii, according to equation (1), are shown in Fig. 1(a) for three disc masses and Schaye's (2004) fiducial critical surface density $\Sigma_c = 5.9\,\mathrm{M_\odot\ pc^{-2}}$($N_{\rm H} = 5.6 \times 10^{20}\ \mathrm{cm^{-2}}$). For the adopted disc masses, the threshold model brackets the observations. Interestingly, the model predicts an increase in $R_{\max}/h_R$ towards small scalelengths. Discs with a higher central surface density form stars out to a larger radius in terms of scalelengths before reaching the critical density. Since, for constant total disc mass, a higher surface density disc has a smaller scalelength, it follows that smaller-scalelength discs have larger $R_{\max}/h_R$. This anticorrelation, which is similar to the observed trend in the Pohlen et al. (2000) sample (Schaye 2004), is also in accordance with the present observations.

Motivated by the observation that the H I gas fraction in the galaxies is small (Kregel, van der Kruit & de Blok 2004, hereafter KKB), we show equation (2) in Fig. 1(b) assuming $\Sigma_c = 5.9\,\mathrm{M_\odot\ pc^{-2}}$ and $(M/L)_\star = 2$ (constant among galaxies). Lower surface brightness discs are predicted to be less extended, with a slope in agreement with the observed trend. The match is better if we take into account that the inferred disc central surface brightnesses are fainter by about 0.7 mag compared to their face-on counterparts (Paper V). The scatter and outliers may be explained as being due to a non-constancy in Σ_c, e.g. due to a varying UV radiation intensity or metallicity, or due to a variation of $(M/L)_\star$. Altogether, the observations are consistent with a 'critical surface brightness' in the range $\Sigma_c/(M/L)_\star = 1.5$–$4\,\mathrm{L_{\odot,\ \mathit{I}}\ pc^{-2}}$. Saying it differently, for $\Sigma_c = 5.9\,\mathrm{M_\odot\ pc^{-2}}$ the stellar mass-to-light ratio is $(M/L)_\star = 4$–$1.5\,\mathrm{M_\odot/L_{\odot,\ \mathit{I}}}$. The lower part of this range is reasonable, both from the perspective of stellar population synthesis (Bell & de Jong 2000) and observations of the stellar velocity dispersions in galaxy discs (Bottema 1997).

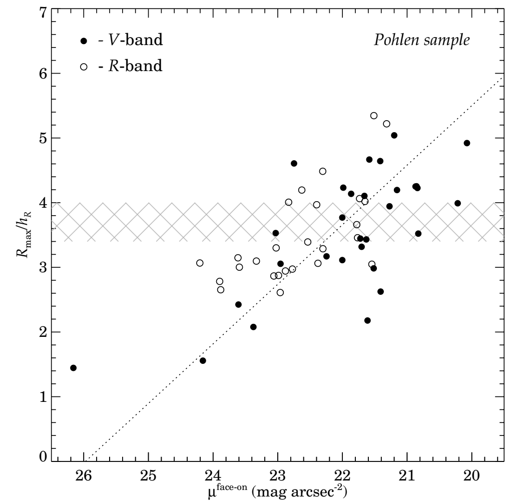

Figure 2. $R_{\max}/h_R$ versus face-on central surface brightness for the *V*- and *R*-band results of Pohlen for the sharply truncated disc model (Pohlen 2001). The face-on surface brightnesses were calculated assuming an exponential vertical luminosity distribution. As in Fig. 1(b), the cross-hatched region shows the prediction of the collapse model and the dotted line shows the prediction of the star-formation threshold model, except that here the $(M/L)_\star$ for the threshold model is arbitrary.

Both models can also be compared to the truncation analysis performed by Pohlen (2001) in the *V* and the *R* bands (Fig. 2). Although obtained using a different method, these data show a trend very similar to our *I*-band result (Fig. 1) and to the star-formation threshold model (dotted line). Lower surface brightness discs tend to be less extended in terms of $R_{\max}$.

It has long been known that viscosity-driven angular momentum redistribution within a star-forming gas disc may drive the resulting stellar disc towards an exponential profile (Lin & Pringle 1987). Depending on the details of star formation, this process may yield a stellar disc with a well-defined edge that advances radially outward with time (Ferguson & Clarke 2001). Unfortunately, the theory has not yet been explicitly investigated with respect to this truncation radius. The theory of stochastic self-propagating star formation predicts $R_{\max}/h_R = 4$ (Seiden, Schulman & Elmegreen 1984) for flat rotation curves. This prediction is similar to that of the collapse model, leading to the same difficulties of predicting no dependence on surface brightness.

4 CONCLUSIONS

At least 20 galaxies in our sample of 34 have truncated stellar discs, displaying a tight relation between disc scalelength and truncation radius. The stellar disc edge seems to occur at a larger number of scalelengths in galaxies with a smaller scalelength, in agreement with the decrease of $R_{\max}/h_R$ towards large scalelengths reported by Pohlen et al. (2000). In addition, we observe a tentative correlation between the ratio $R_{\max}/h_R$ and the de-projected face-on central surface brightness of the disc. These observations appear to have two important implications. First, high surface brightness spirals with small scalelengths, which are the most numerous spirals in the local Universe (de Jong & Lacey 2000), have an $R_{\max}/h_R$ of at least four. Secondly, the face-on disc surface brightness at the truncation radius is roughly constant among galaxies.

The observed truncation radii were compared to the predictions of several theories proposed for its origin. The data are best reproduced by the constant star-formation threshold model for the truncation (Schaye 2004). In particular, this model is able to match the correlation between $R_{\rm max}/h_{\rm R}$ and surface brightness for reasonable stellar mass-to-light ratios. The collapse model for disc-galaxy formation (van der Kruit 1987; DSS97), in which the truncation corresponds to the maximum angular momentum in the protogalaxy before disc collapse with detailed conservation of angular momentum, provides a significantly poorer match to the observations. This model would require some amount of redistribution of angular momentum during and/or after the collapse.

ACKNOWLEDGMENTS

We thank the referee for comments and suggestions.

REFERENCES

Bell E. F., de Jong R. S., 2000, MNRAS, 312, 497
Bottema R., 1996, A&A, 306, 345
Bottema R., 1997, A&A, 328, 517
Broeils A. H., Rhee M.-H., 1997, A&A, 324, 877
Bullock J. S., Dekel A., Kolatt T. S., Kravtsov A. V., Klypin A. A., Porciani C., Primack J. R., 2001, ApJ, 555, 240
Dalcanton J. J., Spergel D. N., Summers F. J., 1997, ApJ, 482, 659 (DSS97)
Davidge T. J., 2003, AJ, 125, 3046
de Grijs R., 1997, PhD thesis, University of Groningen (http://www.ub.rug.nl/eldoc/dis/science/r.de.grijs)
de Grijs R., 1998, MNRAS, 299, 595
de Grijs R., Kregel M., Wesson K., 2001, MNRAS, 324, 1074, (GKW)
de Jong R. S., Lacey C., 2000, ApJ, 545, 781
de Jong R. S., van der Kruit P. C., 1994, A&AS, 106, 451
Demers S., Battinelli P., Letarte B., 2003, AJ, 125, 3037
Drimmel R., Spergel D. N., 2001, ApJ, 556, 181
Fall S. M., Efstathiou G., 1980, MNRAS, 193, 189
Ferguson A. M. N., Clarke C. J., 2001, MNRAS, 325, 781
Florido E., Battaner E., Guijarro A., Garzón F., Jiménez-Vicente J., 2001, A&A, 378, 82
Freeman K. C., 1970, ApJ, 160, 811
Freeman K. C., 2002, in Athanassoula E., Bosma A., eds, ASP Conf. Ser., Vol. 275, Disks of Galaxies: Kinematics, Dynamics and Perturbations. Astron. Soc. Pac., San Francisco, p. 3
Freudenreich H. T., 1998, ApJ, 492, 495
Gunn J. E., 1982, in Longair M. S., Coyne G. V., Bruck H. A., eds, Astrophysical Cosmology. Vatican City: Pontifica Academia Scientiarum, p. 233
Kennicutt R. C., 1989, ApJ, 344, 685
Kregel M., 2003, PhD thesis, Univ. of Groningen (http://www.ub.rug.nl/eldoc/dis/science/m.kregel)
Kregel M., van der Kruit P. C., de Blok W. J. G., 2004, MNRAS, 352, 768 (KKB)
Kregel M., van der Kruit P. C., de Grijs R., 2002, MNRAS, 334, 646 (KKG)
Kregel M., van der Kruit P. C., Freeman K. C. 2004, MNRAS, submitted (Paper V)
Lin D. N. C., Pringle J. E., 1987, ApJ, 320, 87
Mo H. J., Mao S., White S. D. M., 1998, MNRAS, 295, 319
Pohlen M., 2001, Dissertation, Ruhr-Universität, Bochum
Pohlen M., Dettmar R.-J., Lütticke R., Schwarzkopf U., 2000, A&AS, 144, 405
Pohlen M., Dettmar R.-J., Lütticke R., 2000, A&A, 357, 1
Ruphy S., Robin A. C., Epchtein N., Copet E., Bertin E., Fouque P., Guglielmo F., 1996, A&A, 313, L21
Schaye J., 2004, ApJ, 609, 667
Schwarzkopf U., Dettmar R.-J., 2000, A&A, 361, 451
Seiden P. E., Schulman L. S., Elmegreen B. G., 1984, ApJ, 282, 95
van den Bosch F. C., 2001, MNRAS, 327, 1334
van der Kruit P. C., 1979, A&AS, 38, 15
van der Kruit P. C., 1987, A&A, 173, 59
van der Kruit P. C., 1988, A&A, 192, 117
van der Kruit P. C., 2001a, in Funes J. G., Corsini E. M., eds, ASP Conf. Ser., Vol. 230, Galaxy Disks and Disk Galaxies. Astron. Soc. Pac., San Francisco, p. 119
van der Kruit P. C., Searle L., 1981a, A&A, 95, 105 (KS1)
van der Kruit P. C., Searle L., 1981b, A&A, 95, 116 (KS2)
van der Kruit P. C., Searle L., 1982, A&A, 110, 61 (KS3)
Weiner B. J., Williams T. B., van Gorkom J. H., Sellwood J. A., 2001, ApJ, 546, 916

This paper has been typeset from a TEX/LATEX file prepared by the author.